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Dark-state polaritons using spontaneously generated coherence

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Abstract. A three-level atomic system in V-configuration (interacting with a single mode laser field) with parallel transition dipole moments exhibiting spontaneously generated coherence due to quantum interference of decaying channels is considered here for the purpose of storing light pulses. This system is equivalent to (with some restrictions) another three-level system in which ground state is coupled with one of the upper states but the upper states are coupled through a DC field and hence can be used to store electromagnetic pulse using the concept of dark-state-polariton.

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Recently, propagation of electromagnetic pulses and their storage have been extensively studied using a three-level atomic medium in Λ-type configuration [1]. The three-level atomic medium in Λ-type configuration irradiated by a strong coupling field on one of its transitions becomes transparent for a signal field (on another transition) due to electromagnetically induced transparency (EIT) [2]. Adiabatically turning off the coupling field allows signal field to be completely absorbed by the atomic medium. The phenomenon of EIT causes extraordinary change in dispersive properties of the atomic medium [3] which drastically alters the velocity of light pulses [4] and can store such pulses as induced atomic coherence or polarization in the medium [1]. In other words, by changing the coupling field slowly towards zero it is possible to store the signal pulse in the atomic medium and by reapplying (i.e., increasing) the coupling field in the same manner the stored signal field can be released back. This phenomenon of storing the optical pulse in an atomic ensemble has been discussed in terms of the 'dark state polaritons (DSP)' which describes entangled state of photon and atomic polarization [5]. Recently, experimental realizations of such DSP have been demonstrated [1].

A three-level atomic or molecular systems in V-configuration interacting with the vacuum field such that dipole moments of two transitions (from ground state to two upper states) being parallel or nearly parallel can control the spontaneous decay of two excited states due to spontaneously generated coherence (SGC) or quantum interference of decaying channels [6]. Many interesting features arising due to the SGC in a number of atomic and molecular schemes were reported in recent past which could find some very useful applications in laser spectroscopy and other areas of quantum optics. Some such interesting effects are quenching of spontaneous emission, ultra narrow spectral profiles, phase dependent population inversion, phase control of spontaneous emission, and controlling optical bistability to optical multistability behavior etc. [7–9]. We propose that this system can also be used for storing signal field and their retrieval (on demand), i.e., like a quantum field storage device by manipulating the degree of SGC in adiabatic manner. Though the three-level systems in V-configuration with parallel dipole moment exhibit many interesting effects but their practical realization is very difficult as the atomic or molecular systems in V-configuration normally posses dipole moments of two transitions perpendicular to each other. Some experimental efforts were made in past to generate SGC from such system [10] but could not reproduce consistent results [11]. Some related analysis for this kind of experiment was also provided [12].

Many other schemes were proposed to circumvent the experimental difficulties in obtaining the parallel dipole moments [13]. Very recently, another proposal has been given by Ficek and Swain [14] to obtain SGC from a three-level system in V-configuration without needing the parallel dipole moments. This scheme consists of a three-level system with perpendicular dipole moments for the transitions coupling the upper nearly degenerate levels with the ground level. One of the transitions is interacting with a laser field while the upper two levels are coupled by a DC field. It has been demonstrated that this system is equivalent to the usual three-level atomic system in V-configuration with parallel dipole moments of transitions. Such a system can be used for storing signal pulses in the atomic medium and can be manipulated for retrieval of pulses by adiabatically changing either decay

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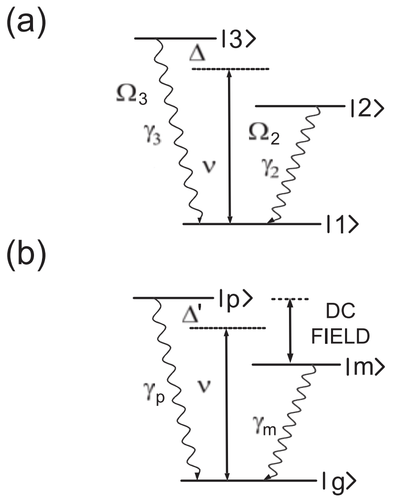

Fig. 1. (a) Schematic diagram of a three-level system in V-configuration interacting with a laser of frequency ν coupled to both the atomic transitions. The associated Rabi frequencies (radiative decay constants) for these transitions are Ω_2, Ω_3 (γ_2, γ_3), respectively. (b) Schematic diagram of an equivalent three-level system . The laser of frequency ν is coupled to only one of the transitions (the symmetric state $|p\rangle$) while a DC field couples the upper two states.

mechanism of lower upper-level or the DC field. In the following we discuss how do we achieve this.

First we describe the dynamical evolution (with and without SGC) of a three-level atom in V-type configuration (Fig. 1a). The system consists of a lower level $|1\rangle$ and two non-degenerate upper levels $|2\rangle$ and $|3\rangle$ interacting with a laser field of frequency ν (we call it quantum field $\hat{E}$). The electric dipole moments of transitions between levels $|1\rangle$ and $|2\rangle$ ($|3\rangle$) is $\vec{\mu}_{21}$ ($\vec{\mu}_{31}$). The upper levels can spontaneously decay to the ground level but any transition between upper levels is forbidden. In the frame rotating with laser frequency ν the density operator equation for such system is given by

$$\dot{\hat{\rho}} = -i[\hat{\rho}, \hat{H}] + \mathrm{L}\hat{\rho}, \tag{1}$$

in which the Hamiltonian is

$$\hat{H} = (\Delta - \omega_{23})\hat{B}_{22} + \Delta\hat{B}_{33} + \left(\Omega_2\hat{B}_{21} + \Omega_3\hat{B}_{31} + H.c.\right), \tag{2}$$

and

$$\begin{aligned}\mathrm{L}\hat{\rho} = &\frac{1}{2}\gamma_2\left(2\hat{B}_{12}\hat{\rho}\hat{B}_{21} - \hat{B}_{22}\hat{\rho} - \hat{\rho}\hat{B}_{22}\right)\\ &+ \frac{1}{2}\gamma_3\left(2\hat{B}_{13}\hat{\rho}\hat{B}_{31} - \hat{B}_{33}\hat{\rho} - \hat{\rho}\hat{B}_{33}\right)\\ &+ \frac{1}{2}\gamma_{23}\left(2\hat{B}_{12}\hat{\rho}\hat{B}_{31} - \hat{B}_{32}\hat{\rho} - \hat{\rho}\hat{B}_{32}\right)\\ &+ \frac{1}{2}\gamma_{23}\left(2\hat{B}_{13}\hat{\rho}\hat{B}_{21} - \hat{B}_{23}\hat{\rho} - \hat{\rho}\hat{B}_{23}\right).\end{aligned} \tag{3}$$

Here $B_{mn} = |m\rangle\langle n|$ is the ladder operator, $\Delta = \omega_{31} - \nu$ is the detuning of the the quantum field frequency from the transition frequency of $|1\rangle$–$|3\rangle$, $\omega_{23} = \omega_{31} - \omega_{21}$ is the frequency difference of the upper two levels. γ_i ($i = 2, 3$) is the spontaneous decay constants of upper levels $|i\rangle$ to the ground level $|1\rangle$. The decay constant arising due to the quantum interference of the two decaying channels is given by

$$\gamma_{23} = \frac{2\sqrt{\omega_{31}^3\omega_{21}^3}}{3\hbar c^3}\vec{\mu_{21}} \cdot \vec{\mu_{31}} = q\sqrt{\gamma_2\gamma_3}. \tag{4}$$

The term γ_{23} depends on the cosine of the angle between two dipole moments through the parameter q. If we have parallel dipole moments then $q = 1$ and the quantum interference or the SGC is maximum. On the contrary, for the perpendicular dipole moments we have $q = 0$ and the SGC vanishes.

We plot absorption-dispersion spectra (under steady state condition) in Figure 2 with and without SGC as a function of detuning of quantum field by numerically

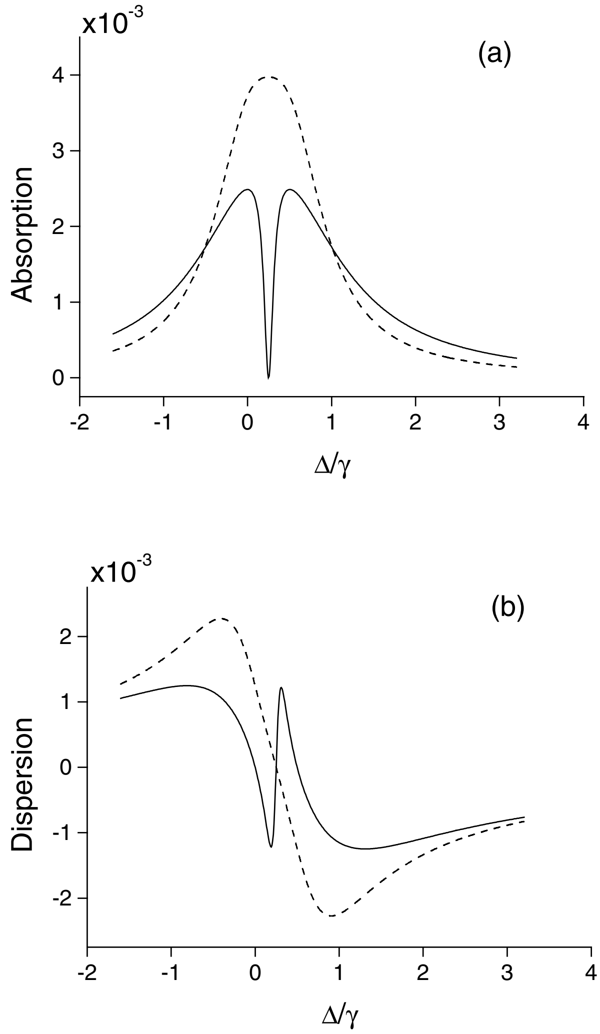

Fig. 2. (a) Absorption (in arbitrary units) curves with (solid curves, $\gamma_{23} = \sqrt{\gamma_2\gamma_3}$) and without (dashed curve, $\gamma_{23} = 0$) SGC. The other parameters are $\gamma_2 = \gamma_3 = \gamma = 0.5$, $\Delta = 0.5$, $\Omega_1 = \Omega_2 = \Omega = 0.05$. (b) Dispersion (in arbitrary units) curves with (solid curves, $\gamma_{23} = \sqrt{\gamma_2\gamma_3}$) and without (dashed curve, $\gamma_{23} = 0$) SGC. The other parameters are same as in (a).

solving equation (1). The parameters chosen are $\gamma_2 = \gamma_3 = \gamma = 0.5$, $\Omega_2 = \Omega_3 = \Omega = 0.05$ and $|\vec{\mu}_{21}| = |\vec{\mu}_{31}|$, resulting into group velocity slowing down. If the dipoles are parallel to each other we observe cancellation of absorption at $\Delta = \omega_{23}/2$ and sharp variation in the refractive index near $\Delta = \omega_{23}/2$. However, if the dipoles are orthogonal to each other then $\vec{\mu_{21}} \cdot \vec{\mu_{31}} = 0$, and we do not observe cancellation of the absorption and no sharp variation of the refractive index near $\Delta = \omega_{23}/2$. Thus it could be possible to use SGC as a control mechanism to vary the group velocity of the light [4] in the atomic medium for storing the signal pulses [5]. However, as discussed above there are practical difficulties in realizing the parallel dipole moments (and achieving adiabatic control of SGC could be much difficult) so we look for an alternative technique using usual perpendicular dipole moments as suggested by Ficek and Swain [14] (and described here briefly for the sake of completeness) for realizing the quantum storage of pulses.

In the following we assume $\gamma_2 = \gamma_3 = \gamma$ and $\Omega_2 = \Omega_3 = \Omega$, for the sake of simplicity and define the symmetric and antisymmetric superposition of the upper states $|2\rangle$ and $|3\rangle$ as

$$|p\rangle = \frac{1}{\sqrt{2}}(|2\rangle + |3\rangle), \quad |m\rangle = \frac{1}{\sqrt{2}}(|2\rangle - |3\rangle). \tag{5}$$

Under the new bases of symmetric and antisymmetric states the master equation (1) can be recast into a slightly different form

$$\dot{\hat{\rho}} = -i\left[\hat{\rho}, \hat{H}\right] + \frac{1}{2}\gamma(1+q)\left(2\hat{B}_{1p}\hat{\rho}\hat{B}_{p1} - \hat{B}_{pp}\hat{\rho} - \hat{\rho}\hat{B}_{pp}\right) + \frac{1}{2}\gamma(1-q)(2\hat{B}_{1m}\hat{\rho}\hat{B}_{m1} - \hat{B}_{mm}\hat{\rho} - \hat{\rho}\hat{B}_{mm}). \tag{6}$$

Correspondingly, the Hamiltonian has also changed to

$$\hat{H} = \Delta'\left(\hat{B}_{pp} + \hat{B}_{mm}\right) - \frac{1}{2}\omega_{23}\left(\hat{B}_{pm} + \hat{B}_{mp}\right) + \sqrt{2}\Omega\left(\hat{B}_{p1} + \hat{B}_{1p}\right), \tag{7}$$

with $\Delta' = \Delta - \omega_{23}/2$.

From the transformation it is clear that the laser field is coupling only to one of the new upper levels (the symmetric state) with the ground level and the new upper-levels are decaying to the ground level independently with two different decay rates as clearly seen from second and third term of equation (6). For parallel dipole moments the parameter $q \cong 1$ and the third term in equation (6) vanishes, which implies that antisymmetric state is metastable. If the upper states $|2\rangle$ and $|3\rangle$ becomes degenerate then there is no coupling between symmetric and antisymmetric states. We can get another physical picture from this model by neglecting the term $\Delta' B_{mm}$. The system now behaves as a three-level configuration in which the ground state $|1\rangle$ is connected to the upper level $|p\rangle$ by the laser field detuned from resonance with this level by Δ' and $|p\rangle$ is also coupled with level $|m\rangle$ by a DC field (Fig. 1b). We can relabel the ground level $|1\rangle$ by $|g\rangle$, the quantum field (in Rabi frequency) as $g\hat{\varepsilon}$ and rewrite the Hamiltonian as

$$\hat{H} = \Delta'\hat{B}_{pp} + D(\hat{B}_{pm} + \hat{B}_{mp}) + g\hat{\varepsilon}(\hat{B}_{pg} + \hat{B}_{gp}), \tag{8}$$

with damping terms in the Liouvillean operator given by

$$\mathrm{L}\hat{\rho} = \frac{1}{2}\gamma_p\left(2\hat{B}_{gp}\hat{\rho}\hat{B}_{pg} - \hat{B}_{pp}\hat{\rho} - \hat{\rho}\hat{B}_{pp}\right) + \frac{1}{2}\gamma_m\left(2\hat{B}_{gm}\hat{\rho}\hat{B}_{mg} - \hat{B}_{mm}\hat{\rho} - \hat{\rho}\hat{B}_{mm}\right). \tag{9}$$

In equation (8), D describes the Rabi frequency of DC field which couples the upper levels and g is the atom-field coupling constant $(=\wp\sqrt{\nu/(2\hbar\epsilon_0 V)})$, $\wp$ is dipole moment of $|g\rangle$ to $|p\rangle$ transition, V is quantization volume. We define quantum field in the slowly varying variable as $\hat{E}(z,t) = \sqrt{\hbar\nu/2\epsilon_0 V}\hat{\varepsilon}(z,t)e^{-\frac{i\nu}{c}(z-ct)}$. For describing the quantum properties of the medium we need collective slowly varying atomic operators $\hat{B}_{xy}(z,t) = (1/N_z)\sum_{j=1}^{N_z}|x_j\rangle\langle y_j|e^{-\omega_{xy}t} = (1/N_z)\sum_{j=1}^{N_z}\tilde{B}_{xy}^j(t)e^{-\omega_{xy}t}$ averaged over small macroscopic volume containing $N_z \gg 1$ atoms at position z. The interaction Hamiltonian can be appropriately recast in the continuous form as

$$\hat{H}_{int} = N\int\frac{dz}{L}\left(g\hat{\varepsilon}(z,t)\hat{B}_{pg} + D\hat{B}_{pm} + H.c.\right), \tag{10}$$

in which N is number of atoms and L is the length of the sample. Note that the new decay constants are related to the orientation of the two dipole moments by

$$q = \cos(\theta) = (\gamma_p - \gamma_m)/(\gamma_p + \gamma_m). \tag{11}$$

As mentioned earlier, q is a measure of quantum interference. If $\gamma_m \ll \gamma_p$ then the level $|m\rangle$ behaves as metastable level and this happens only when we have maximum quantum interference or SGC ($q \cong 1$) in the system (of Fig. 1a). This system (Fig. 1b) defined by equations (6) and (7), is then unitarily equivalent to the previous system (Fig. 1a) where dipoles are presumed to be parallel. Using equations (8) and (9) we can write down explicitly the equation of motion for each component of the density operator in the following way:

$$\begin{aligned}
\dot{\tilde{B}}_{pp} &= -ig\hat{\varepsilon}(\tilde{B}_{gp} - \tilde{B}_{pg}) - iD(\tilde{B}_{mp} - \tilde{B}_{pm}) - \gamma_p\tilde{B}_{pp},\\
\dot{\tilde{B}}_{mm} &= iD(\tilde{B}_{mp} - \tilde{B}_{pm}) - \gamma_m\tilde{B}_{mm},\\
\dot{\tilde{B}}_{gg} &= ig\hat{\varepsilon}(\tilde{B}_{gp} - \tilde{B}_{pg}) + \gamma_p\tilde{B}_{pp} + \gamma_m\tilde{B}_{mm},\\
\dot{\tilde{B}}_{pg} &= -(i\Delta' + \gamma_p/2)\tilde{B}_{pg} - ig\hat{\varepsilon}(\tilde{B}_{gg} - \tilde{B}_{pp}) - iD\tilde{B}_{mg},\\
\dot{\tilde{B}}_{mg} &= -(i\Delta' + \gamma_m/2)\tilde{B}_{mg} + ig\hat{\varepsilon}\tilde{B}_{mp} - iD\tilde{B}_{pg},\\
\dot{\tilde{B}}_{pm} &= -(\gamma_p/2 + \gamma_m/2)\tilde{B}_{pm} - ig\hat{\varepsilon}\tilde{B}_{gm} - iD(\tilde{B}_{mm} - \tilde{B}_{pp}).
\end{aligned} \tag{12}$$

The field propagation equation (in direction z) for the quantum field in slowly varying amplitude approximation goes as

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right)\hat{\varepsilon}(z,t) = igN\tilde{B}_{gp}(z,t). \tag{13}$$

In the low intensity approximation of the quantum field, i.e., if the ratio of Rabi frequencies $g\hat{\varepsilon}/D \ll 1$, it is easy to show that system described by equation (12) exhibit prominent electromagnetically induced transparency (EIT) provided one can manipulate the decay constant γ_m. For the weak quantum field and using perturbation theory in equation (12), it is easy to show that

$$\tilde{B}_{gp}^{(1)} \sim \frac{ig\hat{\varepsilon}}{\gamma_p/2 - i\Delta' + \frac{D^2}{\gamma_m/2 - i\Delta'}}. \tag{14}$$

Clearly, equation (14) exhibits EIT kind of behavior (as depicted in Fig. 2) and such behavior is very sensitive function of γ_m. For a fixed γ_P, if the quantum interference is maximum ($\cos(\theta) \cong 1$) then $\gamma_m \cong 0$ and equation (14) shows maximum zero absorption (or prominent EIT behavior) at resonance which becomes less and less prominent as $\cos(\theta)$ approaches 0 or there is no SGC in the system. Hence, SGC can control the EIT-like characteristics of the system and should be useful in storage of quantum field in such atomic ensembles. However, to realize manipulation of SGC in any practical physical system is very difficult and alternative to this could be the manipulation of D. If there is no DC field D then also zero absorption at resonance is withdrawn. In other words, the interaction between symmetric and antisymmetric states vanishes. We thus propose that such a system is suitable for storing the electromagnetic field pulses by manipulation of the DC field very slowly. In the following we give essential details to show how this system acts [5] as quantum memory for the sake of completeness. We use perturbation theory with the assumption that $\tilde{B}_{gg} = 1$ and remaining all other elements equal to zero in zeroth order. Further to this we set $\gamma_m \sim 0$ (meaning state $|m\rangle$ to be metastable in the system of Fig. 1b), which implies maximal quantum interference, i.e., $\cos(\theta) \cong 1$ in the original system of Figure 1a, useful in avoiding information losses and one can have a reasonable storage timing. Then in first order (assuming $\Delta' = 0$) it is easy to show that

$$\begin{aligned}\tilde{B}_{gp} &= \frac{-i}{D}\frac{\partial}{\partial t}\tilde{B}_{gm},\\ \tilde{B}_{gm} &= -\frac{g\hat{\varepsilon}}{D} - \frac{i}{D}\left[\left(\frac{\partial}{\partial t} + \frac{\gamma_p}{2}\right)\left(\frac{-i}{D}\frac{\partial}{\partial t}\hat{B}_{gm}\right) + \hat{F_{gp}}\right],\end{aligned} \tag{15}$$

in which we have incorporated the δ-correlated Langevin noise operator $\hat{F}_{pg}$ such that $\langle \hat{F}_{xy}(t)\hat{F}_{x'y'}(t')\rangle \sim K\delta(t-t')$ etc., where K is a constant. We further assume adiabatic condition [5] or slow change for D in time such that we have the surviving term

$$\tilde{B}_{gm} \cong -\frac{g\hat{\varepsilon}(z,t)}{D} \tag{16}$$

and the propagation equation becomes

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right)\hat{\varepsilon}(z,t) = -\frac{g^2N}{D^2}\frac{\partial}{\partial t}\hat{\varepsilon}(z,t). \tag{17}$$

Which states that there is group velocity modification of the quantum field given by

$$v_g = \frac{c}{(1 + g^2N/D^2)}. \tag{18}$$

If we introduce a quantum field assuming the following transformation

$$\hat{\psi}(z,t) = \cos(\phi)\hat{\varepsilon}(z,t) - \sin(\phi)\sqrt{N}\tilde{B}_{gm}(z,t), \tag{19}$$

where

$$\cos(\phi) = \frac{D}{\sqrt{D^2 + g^2N}},$$
$$\sin(\phi) = \frac{g\sqrt{N}}{\sqrt{D^2 + g^2N}},$$

then it is straightforward to show [5] that $\hat{\psi}(z,t)$ satisfy the following equation under the adiabaticity condition

$$\left(\frac{\partial}{\partial t} + c\,\cos^2(\phi)\frac{\partial}{\partial z}\right)\hat{\psi}(z,t) = 0, \tag{20}$$

which describes shape preserving propagation with velocity $v = v_g(t) = c\cos^2(\phi)$. The name given to $\hat{\psi}(z,t)$ is a polariton (or Bosonic quasi particle) as it satisfies the Bosonic commutation relationship [5]. Also, $\hat{\psi}(z,t)$ are eigen functions of the interaction Hamiltonian with eigen values zero and for this reason the quasi-particle are called by dark-state-polariton (DSP). The DSP is the key element of quantum memory. By adiabatic change of ϕ from 0 to $\pi/2$ it is possible to decelerate and stop an input quantum field pulse. By doing so the quantum field of the light is mapped onto collective polarization of the atomic medium. The DSP can be accelerated back to the speed of light c by re-changing the ϕ very slowly and thus the stored polarization state of the atomic system transferred back to the field. The adiabatic variation of ϕ is provided by adiabatically varying the Rabi frequency D. Since in the model under discussion, D is related to a DC field, so by changing DC field in very slow manner one can get the desired variation of ϕ to store light pulse in the atomic medium and their retrieval using the concept of DSP. This means that the system which is unitarily equivalent of a V-system with SGC can be used for storing and retrieval of light pulses with the concept of DSP.

In conclusion, we have proposed a scheme utilizing spontaneously generated coherence (SGC) for storing light pulses in an ensemble of three-level system in V-configuration. However, the practical realization of the SGC scheme is difficult so we adopt the alternative methodology of using three-level system with a DC field, which is unitarily equivalent to our original scheme and very much similar to reference [14] with lower upper level to be metastable (meaning almost maximum SGC in the original scheme) to have reasonable storage time for the information. Such a scheme can easily be realized using rubidium atoms [15] or solid state system of Pr^{3+}:$YAlO_3$ [16].

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